CONTROL OF OUTPUT BEAM DIVERGENCE IN A SEMICONDUCTOR WAVEGUIDE DEVICE

The present invention relates to semiconductor waveguide devices, and in particular to methods for controlling the optical output beam divergence therefrom.

The invention has particular, though not exclusive, use in the manufacture of semiconductor lasers, amplifiers, modulators and other waveguides suitable for use in telecommunications and printing applications where low coupling loss to other optical components (such as optical waveguides) and high kink-free power output is required. More particularly, the invention has particular, though not exclusive, use in the manufacture of 980 nm pump lasers for telecommunications applications, and in the manufacture of 830 nm high power lasers for printing applications.

Conventional semiconductor lasers generally provide an optical output beam of substantially elliptical cross-section. With reference to figure 1, such conventional lasers typically comprise a succession of layers formed on a substrate 10, to include a lower cladding layer 11, an optically active core region 12 and an upper cladding layer 13. In a conventional ridge type laser, lateral optical confinement is effected by way of a ridge waveguide 14 upon which suitable electrical contact material 15 may be deposited with which to provide electrical injection to drive the lasing mode. The resultant optical output beam 16 emerges from the output end 17 along the longitudinal or z-axis as shown.

The core region 12 typically comprises a plurality of layers, such as a central layer 12a defining the quantum well and two or more outer layers 12b, 12c with composition varying as a function of depth within the layer to provide a

so-called graded index separate confinement heterostructure (GRINSCH) core region 12.

The structure of figure 1 provides a conduction band edge profile as shown in figure 2, in which the cladding region 20 corresponds to the lower cladding layer 11; the cladding region 24 corresponds to the upper cladding layer 13; the quantum well region 22 corresponds to the central layer 12a; and the graded index regions 21 and 23 respectively correspond to the outer layers 12b, 12c.

The output beam 16 (figure 1) from this structure typically has a beam divergence in the vertical direction (shown in the figure as the y-direction) of the order of between 30 and 40 degrees, resulting in a large vertical far field. Vertical direction is generally defined as the wafer growth direction, i.e. the direction that is orthogonal to the plane of the substrate, as shown. By contrast, beam divergence in the horizontal or lateral direction (shown in the figure as the x-direction) is typically of the order of between 5 and 10 degrees.

The very large far field and asymmetry of the far fields in the vertical and horizontal directions cause a number of problems such as high coupling loss to optical components downstream of the laser output 17 (such as optical fibres) and particularly low coupling tolerance between the laser and a single mode fibre (which requires a circular beam profile).

A number of techniques have been proposed to reduce the far field or beam divergence in the vertical direction and hence to reduce the asymmetry in far field output. The vertical far field can be reduced to some degree by simply reducing the thickness of the core region 12. However, in this case, optical overlap with the quantum well 12a is also reduced which in turn increases

the laser threshold current and cavity loss occurs from losses associated with intervalence band absorption. In addition, it becomes more difficult to achieve high kink-free emission power due to the occurrence of higher mode lasing at high current injection levels.

A number of different approaches have been proposed to provide 'mode-shaping' layers that reduce far field into the semiconductor laser structure.

For example, US 5,815,521 describes a laser device in which a mode-shaping layer is introduced into each one of the cladding layers. Each of the mode-shaping layers comprises a layer of increased refractive index relative to the rest of the respective cladding layer, to form a conduction band edge profile as shown in figure 1 of US '521. It is noted that the mode-shaping layers each comprise a localised step change in band energy level.

US 5,923,689 describes another technique in which a pair of passive waveguides of reduced refractive index is provided on either side of the quantum well structure, separated therefrom by a barrier layer. A similar structure, this time also in conjunction with a graded index confinement structure, is also shown in "Semiconductor lasers with unconventional cladding structures for small beam divergence and low threshold current" by Shun-Tung Yen *et al*, Optical and Quantum Electronics 28 (1996) pp. 1229-1238. Both of these documents advocate a step-wise local reduction in refractive index within the cladding layers.

"Design and fabrication of 980nm InGaAs/AlGaAs quantum well lasers with low beam divergence" by Guowen Yang *et al*, SPIE Vol. 2886 (1996), pp. 258-263 describes the insertion of two low refractive index layers inserted between the cladding and graded index layers to decrease beam divergence in the vertical direction.

"980 nm InGaAs/AlGaAs quantum well lasers with extremely low beam divergence" by Shun-Tung Yen *et al*, Proceedings of Semiconductor Laser Conference (1996), 15th IEEE International, pp. 13-14 also describes the introduction of two low refractive index layers respectively adjacent to the graded index layers also to reduce the vertical far field distribution.

US 6,141,363 contemplates the reduction of beam divergence by means of a plurality of layers within the core region, of alternating high and low refractive index.

It is an object of the present invention to provide a semiconductor waveguide device with reduced beam divergence in the vertical direction.

According to one aspect, the present invention provides a semiconductor optical waveguiding device comprising:

a first cladding layer;

a second cladding layer; and

a waveguiding layer disposed between the first and second cladding layers and having a substantially higher refractive index than said first and second cladding layers;

wherein at least one of the first and second cladding layers includes a beam control layer in which a property of the semiconductor material varies as a function of depth through the layer, the beam control layer including a first sub-layer in which the property varies gradually from a first level to a second level, and a second sub-layer in which the property varies gradually from said second level to a third level.

According to another aspect, the present invention provides a method of forming a semiconductor optical waveguiding device comprising the steps of:

forming a first cladding layer on a substrate;

forming a waveguiding layer on said first cladding layer, the waveguiding layer having a refractive index substantially greater than the first cladding layer;

forming a second cladding layer on said waveguiding layer, the second cladding layer having a refractive index substantially less than the waveguiding layer; and

during the step of forming said first cladding layer, forming a beam control layer therein by gradually modifying deposition conditions so as to vary a property of the semiconductor material as a function of depth through the beam control layer, such that the beam control layer includes a first sub-layer in which the property varies gradually from a first level to a second level, and a second sub-layer in which the property varies gradually from said second level to a third level.

Embodiments of the present invention will now be described by way of example and with reference to the accompanying drawings in which:

Figure 1 illustrates a conventional semiconductor laser device with a ridge waveguide;

Figure 2 is a schematic diagram of the conduction band edge of the semiconductor device of figure 1;

Figure 3 illustrates a semiconductor laser device having a far-field reduction layer according to a presently preferred embodiment of the present invention;

Figure 4 is a schematic diagram of the conduction band edge of the device of figure 3;

Figure 5 is a graph showing a comparison of the near field optical intensity distributions of the respective optical outputs of the laser devices of figures 1 and 3 as a function of y-position;

Figure 6 is a graph showing a comparison of the far field optical intensity distributions of the respective optical outputs of the laser devices of figures 1 and 3 as a function of y-position;

Figure 7 is a graph showing fundamental transverse mode light intensity output as a function of drive current for the laser of figure 3;

Figure 8 is a graph showing second order transverse mode light intensity output as a function of drive current for the laser of figure 3;

Figure 9 is a graph showing fundamental transverse mode light intensity output as a function of drive current for the laser of figure 1;

Figure 10 is a graph showing second order transverse mode light intensity output as a function of drive current for the laser of figure 1;

Figure 11 is a schematic diagram of refractive index profile as a function of depth (y direction) in a first configuration of device of figure 3;

Figure 12 is a schematic diagram of refractive index profile as a function of depth in a second configuration of device of figure 3;

Figure 13 is a schematic diagram of refractive index profile as a function of depth in a third configuration of device of figure 3;

Figure 14 is a schematic diagram of refractive index profile as a function of depth in a fourth configuration of device of figure 3;

Figure 15 is a schematic diagram of refractive index profile as a function of depth in a fifth configuration of device of figure 3;

Figure 16 is a schematic diagram of refractive index profile as a function of depth (y direction) in a sixth configuration of device of figure 3;

Figure 17 is a schematic diagram of refractive index profile as a function of depth in a seventh configuration of device of figure 3; and

Figure 18 is a schematic diagram useful in illustrating the principles of varying refractive index in a semiconductor material using superlattice structures.

With reference to figure 3 a preferred configuration of device according to the present invention is shown schematically. A substrate 30 supports a lower cladding layer 31, an optically active core region 32 and an upper cladding layer 33. In the preferred arrangement, a ridge waveguide 34 provides lateral optical confinement. A suitable electrical contact material 35 may be deposited onto the ridge 34 with which to provide electrical injection to drive the lasing mode.

It is noted that the principles of the present invention may be applied to laser diodes having other forms of structure providing lateral optical confinement, such as a buried heterostructure laser. It is also noted that the principles of the present invention may also be applied generally to a semiconductor waveguiding structure other than a laser diode. More generally, the principles can be applied in active and passive optical devices with laterally confining waveguide structures. These include amplifiers, modulators and passive waveguides such as those integrated onto a single substrate to form an integrated optical device.

The resultant optical output beam 36 emerges from the output end 37 along the longitudinal or z-axis as shown.

The core region 32 preferably comprises a plurality of layers, such as a central layer 32a defining the quantum well and two or more outer layers 32b, 32c in which the composition varies as a function of depth within the layer to provide a graded index separate confinement heterostructure (GRINSCH) core region 32. However, it will be understood that the

invention has applicability to laser devices not utilising a graded index core region.

The lower cladding layer 31 incorporates a far field reduction layer ('FRL') or beam control layer 38. To this end, the lower cladding layer comprises two sub-layers 31a, 31b, between which is formed the beam control layer 38. The beam control layer 38 comprises at least two sub-layers 38a, 38b each formed from semiconductor material whose properties vary gradually through the thickness thereof in a manner to be described in more detail hereinafter.

The structure of figure 3 provides a conduction band edge profile as shown in figure 4. The lower cladding region 40 to 43 corresponds to the lower cladding layer 31. More specifically, the region 40 corresponds to the lower cladding sub-layer 31a; the region 43 corresponds to the lower cladding sub-layer 31b; the region 41 corresponds to the lower beam control sub-layer 38a; and the region 42 corresponds to the upper beam control sub-layer 38b. The cladding region 47 corresponds to the upper cladding layer 33; the quantum well region 45 corresponds to the central layer 32a; and the graded index regions 44 and 46 respectively correspond to the outer layers 32b, 32c.

In a particularly preferred embodiment of 830 nm laser, the layer structure of the laser device is as given below:

Layer No	Ref, figs 3 & 4	Material (x,y)	Composition	Thickness (μm)	Type	Dopant
15	39	GaAs		0.100	p	Zn
14	33, 47	Al(x)GaAs	0.35>0.05	0.120	p	Zn
13	33, 47	Al(x)GaAs	0.35	1.700	p	Zn
12	33, 47	Al(x)GaAs	0.35	0.200	p	Zn

11	32c, 46	Al(x)GaAs	0.22 > 0.35	0.120		U/D
10	32a, 45	(AlxGa)In(y)As	x=0.14, y=0.14	0.008		U/D
9	32b, 44	Al(x)GaAs	0.30> 0.22	0.070		U/D
8	32b, 44	Al(x)GaAs	0.33 > 0.30	0.030	n	Si
7	32b, 44	Al(x)GaAs	0.35 > 0.33	0.020	n	Si
6	31b, 43	Al(x)GaAs	0.35	0.625	n	Si
5	38b, 42	Al(x)GaAs	0.27>0.35	0.320	n	Si
4	38a, 41	Al(x)GaAs	0.35>0.27	0.320	n	Si
3	31a, 40	Al(x)GaAs	0.35	1.400	n	Si
2	31a	Al(x)GaAs	0.05 > 0.35	0.210	n	Si
1	30	GaAs		0.500	n	Si

The respective layers of figures 3 and 4 are referenced in column 2 of the above table.

The structure is grown on a GaAs substrate (first layer) with an 8 nm thick InGaAlAs compressively strained quantum well (tenth layer) for 830 nm laser applications using MOCVD or MBE deposition techniques. The quantum well 32a, 45 is surrounded on both sides by 120 nm graded index separate confinement hetero structure layers 32b, 32c, 44, 46 (the 7th to 9th and 11th layers). The third and sixth layers are the lower cladding sub-layers 31a, 31b, and the 12th and 13th layers are the upper cladding layer 33, 47. The fourth and fifth layer are the beam control sub-layers for far field reduction. These layers are also used to suppress higher mode lasing and therefore to enhance kink free power.

The thicknesses of the 4th, 5th and 6th layers as well as the mole fraction of Al at the middle point of the 4th and 5th layers are, in this embodiment, optimized such that all the following criteria are achieved:

i) full width at half maximum (FWHM) of vertical far field is about 21 degrees;

ii) optical overlap reduction due to the beam control layer is very insignificant;

iii) excellent device performance for wafer growth tolerance of ±10% of layer thickness, and ±1% of layer mole fraction;

iv) significant suppression of higher mode lasing.

Device fabrication can be performed using conventional photolithographic techniques and dry or wet etch, followed by wafer thinning and metal contact deposition.

Figures 5 and 6 show simulated near field intensity distribution and far field distribution for the fundamental mode of a 2.5 mm wide ridge laser, as a function of y position, with and without the beam control layers 38a, 38b, 41, 42.

In figure 5, the dotted line represents the near field intensity distribution without beam control layer and the solid line represents the near field intensity with beam control layer. It can be seen that the beam control layer has little impact on the near field intensity distribution. However, in figure 6, the dotted line represents the far field intensity distribution without beam control layer and the solid line represents the far field intensity distribution with beam control layer. It can be seen that the beam control layer has substantial impact on the intensity distribution, providing a much narrower peak with substantially greater intensity maximum.

The etching of the ridge 34 of the laser device plays an important role in the device's kink-free power and the ellipticity of the output beam, as higher mode lasing and horizontal far field are strongly dependent on the etch step.

Comparison can be made between devices processed using structures with and without the beam control layer. In order to make the comparison more meaningful, the criteria for the same horizontal far field are used. In this case, devices processed on the structure with mode control need to be etched to a depth 50 nm greater than those processed without the mode control layers. The comparisons are shown for a device having a 2.2 mm wide ridge and a 1.2 mm long cavity.

Figure 7 shows the laser power as a function of drive current for the fundamental (first) mode in a device with the beam control layer 38a, 38b. Figure 9 shows laser power as a function of drive current for the fundamental mode in a corresponding device without the beam control layer. It can be seen that there is substantially no difference.

However, figure 8 shows the laser power as a function of drive current for the higher (second) mode in a device with the beam control layer 38a, 38b. Figure 10 shows laser power as a function of drive current for the higher mode in a corresponding device without the beam control layer. It can be seen that there is a huge difference of device performance in terms of higher mode lasing. More particularly, for the device structure with beam control layers, no power kink is observed for injection current up to 600mA, while in the case of the device structure without beam control layers, the power kink occurs when injection current reaches only 175 mA.

The prior art generally proposes mode control layers that include a step discontinuity in the refractive index of the cladding layers. In the present invention, it has been discovered that the use of a graded beam control layer, and in particular, the use of a V-profile beam control layer, provides substantial improvements in device performance. Another advantage is that

with the graded beam control layer of the present invention, much less tight control of growth conditions is required to achieve the desired mode control.

This is demonstrated in the following table which shows the variations in vertical far field and optical overlap as a function of 1% changes in mole fraction of Al, for both devices without beam control layers and with the beam control layers. Variations in both vertical far field and optical overlap are much more tightly controlled in the present invention.

With mode control layer			Without mode control layer		
Mole fraction of Al	Vertical far field (°)	Optical overlap (%)	Mole fraction of Al	Vertical far field (°)	Optical overlap (%)
26%	19.4	1.86	30%	17.3	1.58
27%	21.4	2.26	31%	21.4	2.36
28%	23.6	2.38	32%	25.7	2.46

Another advantage of the V-profile beam control layer is that it can eliminate possible problems with carrier trapping in the beam control layer leading to better carrier transportation and improved L-I (light intensity versus drive current) slope efficiency.

The embodiment described above illustrates the use of a beam control layer 38 in which the first (lower) cladding layer 31 incorporates two beam control sub-layers 38a, 38b in which a physical property (the stoichiometric ratio) of the semiconductor material varies as a function of depth (y) through each of the sub-layers 38a, 38b so as to vary an electronic property (the conduction band edge) and an optical property (the refractive index) of the sub-layer respective sub-layer.

More particularly, the physical property of the beam control sub-layers 38a, 38b varies so as to provide a substantially linear decrease, then increase, in conduction band edge 41, 42 in the beam control layer 38 to provide a substantially 'V' shaped profile. However, it is to be understood that the profile may be varied.

A non-exhaustive selection of possible refractive index versus depth profiles for beam control layers are shown in figures 11 to 17. In figure 11, the refractive index profile corresponds substantially to the conduction band edge profile illustrated in figure 4, comprising: (i) low refractive index lower cladding region 110; (ii) lower beam control sub-layer region 111 having a linearly increasing refractive index as a function of y; (iii) lower bean control sub-layer region 112 having a linearly decreasing refractive index as a function of y; low refractive index lower cladding region 113; graded index confinement regions 114 and 116; quantum well region 115; and upper cladding region 117.

More generally, the beam control layer includes a first sub-layer 38a in which the physical property varies gradually from a first level to a second level, and a second sub-layer 38b in which the physical property varies gradually from said second level to a third level, as exemplified by each one of the refractive index profiles of figures 11 to 17.

The third level may be the same as the first level, such that the lower cladding sub-layers 31a and 31b have substantially the same physical properties, as in figures 11 to 15 and 17. Alternatively, one part of the cladding region (e.g. 110) may have a different refractive index value to that of the other part of the cladding region (e.g. 113). More particularly, the lower (or outermost) part of the cladding region (e.g. 110) may have a lower

refractive index value than the other part of the cladding region (e.g. 113) as shown in figure 16.

The physical property may vary in a non-linear manner so as to provide a non-linear variation in conduction band edge and/or refractive index as a function of depth through the first and second sub-layers. Such an arrangement is shown in figure 13 where the first sub-layer 131 of the beam control layer has a gradually increasing refractive index in which the increase is non-linear. Similarly, the second sub-layer 132 of the beam control layer has a gradually decreasing refractive index in which the decrease is non-linear.

The beam control sub-layers 38a and 38b may be contiguous, i.e. without further sub-layers in between as in figures 11 and 13 to 17. However, in another embodiment, the beam control sub-layers 38a, 38b may be separated by a further sub-layer, e.g. to provide a flat-bottomed V-profile in the conduction band edge, or flat topped inverted V-profile in the refractive index, as shown in figure 12. In figure 12, the beam control layer provides a lower beam control sub-layer 121 of gradually increasing refractive index, an upper beam control sub-layer 123 of gradually decreasing refractive index, and an intermediate beam control sub-layer 122 of substantially constant refractive index.

The beam control layer 38 may be provided within the lower cladding layer 31, the upper cladding layer 33, or in beam control layers may be provided in both lower and upper cladding layers. This latter example is illustrated by the refractive index profile in figure 14. Figure 14 shows a first beam control layer comprising sub-layers 141, 142 within the lower cladding layer 140, 143, and a second beam control layer comprising sub-layers 145, 146 within the upper cladding layer 144, 147.

The beam control layer may be located in the cladding layer immediately adjacent to the quantum well structure or GRINSCH structure as illustrated in figure 17. In figure 17, beam control sub-layer regions 171, 172 are located between the lower cladding region 170 and the GRINSCH region 173.

As previously mentioned, the lateral optical confinement structure, e.g. quantum well region 115 need not be sandwiched between graded index confinement regions 114, 116 (e.g. figure 11). As shown in figure 15, the quantum well region 115 may be sandwiched between stepped index confinement regions 154, 156.

The beam control layer can generally be deployed in either p-cladding layers or n-cladding layers, although n-cladding layers is preferred since it does not affect any cladding etch process.

An important aspect of the present invention is the use of a beam control layer in the cladding layer that has a gradually varying property rather than a single large step change. The gradual change occurs through a thickness of at least 50 nm in the beam control layer. More preferably, the gradual change in property occurs in a first direction over a beam control sub-layer of at least 100 nm thickness, and then in a second direction opposite to the first direction over a beam control sub-layer of at least 100 nm thickness.

It is noted that this 'gradual change' is effectively defined relative to the optical wavelength of the light passing therethrough. It is also possible to create such a gradual change in refractive index in a semiconductor layer by building a superlattice type structure or digital alloy in which alternating layers of low and high refractive index material are formed with a localised

average thickness ratio that defines the effective refractive index over a dimension of the order of one wavelength of light or less. The principle of this is illustrated in figure 18.

Thus, a succession of step changes 180 between sub-layers of low 182 and high 181 refractive index material in which each sub-layer has a thickness substantially less than the wavelength of light can effect a gradual change in refractive index by slowly varying the ratio of high to low sub-layer thicknesses as indicated by sub-layers 183, 184. The net effect is a corresponding gradual change in refractive index 185 as seen by the light propagating within the layer.

It will also be understood that the gradual change can generally be effected by a 'staircase'-type succession of small, stepwise increments or decrements in the material property (e.g. refractive index) to form the beam control layer, with each successive step being of thickness substantially less than the wavelength of light propagating in the layer.

In presently preferred embodiments, the gradual change in refractive index results in a change in refractive index of at least 0.1 % in a beam control sub-layer over at least 100 nm thickness

In the preferred embodiments, over the range of desired changes in refractive index, the corresponding changes in bandgap profile and semiconductor material composition are related thereto in a substantially linear fashion.

The invention has applicability to a wide range of semiconductor materials systems in particular, though not exclusively, those listed in the table below.

Quantum well material	Barrier material	Cladding material	Substrate
InGaAs	AlGaAs	AlGaAs	GaAs
GaAs	AlGaAs	AlGaAs	GaAs
InGaAlAs	AlGaAs	AlGaAs	GaAs
InGaAs	InGaP	InGaAlP	GaAs
InGaAs	GaAs	InGaP	GaAs
InGaAs	InGaAsP	InGaP	GaAs
InGaAsN	AlGaAs	AlGaAs	GaAs
InGaAsP	InGaAsP	InP	InP
InGaAlAs	InGaAlAs	InP	InP

Other embodiments are intentionally within the scope of the appended claims.